X-602-75-58

PREPRINT

NASA TM X- 70848

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(NASA-TM-X-70848) ON THE ORIGIN OF COSMIC RAYS (NASA) 14 p HC $3.25 CSCL 03B

N75-19120

Unclas

G3/93 13276

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MARCH 1975

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GREENBELT, MARYLAND

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ON THE ORIGIN OF COSMIC RAYS

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ABSTRACT

Using recent surveys of molecular clouds and γ-rays in the galaxy, it has become possible to determine the distribution of 1 to 10 GeV cosmic-ray nucleons in the galaxy. This distribution appears to be identical to the supernova remnant distribution to within experimental error, providing strong support for the hypothesis that supernovae produce most of the observed cosmic rays. This distribution resembles that of OB associations of average age ~30 million years suggesting that cosmic rays are produced by population I objects about 30 million years after their birth.

The problem of the origin of cosmic rays has been the central problem of high energy astrophysics for over a generation. Over four decades have passed since Baade and Zwicky (1934) first proposed that supernova explosions could provide the energy for accelerating cosmic rays. The supernova origin hypothesis gained observational support in the early 50s when, shortly after, Shklovskii (1953) proposed that cosmic-ray electrons radiating in the magnetic field of the Crab Nebula produced its optical continuum radiation. This suggestion led to the prediction that such synchrotron radiation should be linearly polarized (Gordon 1954, Ginzburg 1954), and shortly thereafter such polarization was indeed detected (Dombrovskii 1954, Oort and Walraven 1956, Pikel'ner 1956). It became apparent that cosmic-ray electrons were present in the Crab Nebula and it was natural to assume that protons and nuclei of cosmic-ray energy were produced there also. The recent unambiguous detection of 100 MeV γ-rays from the Crab Nebula and the Vela supernova remnant has provided evidence that these two young, nearby remnants produce cosmic rays (Share 1973, Fazio 1973, Kniffen et al. 1974, Thompson et al. 1974). The nature of the γ-ray emission from these objects as to whether nucleons are indeed involved, however, needs further observational clarification. Also, the question has been raised as to whether one can consider the Crab Nebula to be a typical galactic supernova remnant and to extrapolate to the conclusion that galactic supernovae are the main source of the observed cosmic rays (Brecher and Burbidge 1972).

Shortly after the discovery of the 3K microwave blackbody background radiation, it was first noted by Fazio, Stecker and Wright (1966) that such radiation precluded the existence of cosmic-ray electrons outside the galaxy with the same intensity as that observed locally. They noted that such electrons would produce more 100 MeV γ-rays than observed if their distribution extended more than ~30 kpc from the earth. Thus, it became apparent that cosmic-ray electrons were of galactic origin.

It was further noted by Greisen (1966) and Zatsepin and Kuz'min (1966) that the blackbody background radiation would interact with ultrahigh energy cosmic rays of extragalactic origin to produce a cutoff in their energy spectrum. The lack of an observed cutoff allowed one to rule out the universal origin hypothesis for ultrahigh energy cosmic rays and to place limits on the extent of their source region as being within 300 Mpc (Stecker 1968). Galactic origin of even ultrahigh energy cosmic rays has been advocated (Stecker 1971, Syrovatskii 1971) and support of this hypothesis has been recently provided by indications of the anisotropy of ultrahigh energy cosmic rays (Krasilnokov et al. 1974, Hillas and Ouldridge 1975).

Attempts to place limits on the extragalactic cosmic-ray flux using the γ-ray background observations have not been conclusive. They still allow a universal cosmic-ray nucleon flux provided the mean intergalactic gas density $n_{IG} \lesssim 10^{-7}$ cm^{-3} and allow origin within the local supercluster even if $n_{IG} \simeq 10^{-5}$ cm^{-3} (Stecker 1975). Thus, the discussion of the extragalactic versus galactic origin hypothesis has continued down to the present (Brecher and Burbidge 1972, Ginzburg 1974).

It has long been realized that observations of galactic γ-rays could provide important information for resolving this problem, but until now it has not been possible because of insufficient γ-ray data and an incomplete knowledge of the amount and distribution of an important component of the interstellar gas, viz., molecular hydrogen. Recent observations of the large-scale galactic distribution of γ-radiation (Fichtel et al. 1975) and molecular clouds (Scoville and Solomon 1975) have now made it possible to investigate the large-scale distribution of galactic cosmic rays. Using the new observations, Stecker et al. (1975) have determined that the cosmic-ray distribution in the galaxy is not uniform as would be indicated by the extragalactic origin hypothesis. These results indicated that there is a weak correlation of the cosmic-ray flux with gas density (mostly H_2 clouds) in the inner part of the galaxy. Also apparent was a falloff of the cosmic-ray flux in the outer galaxy (also found by Dodds, Strong and Wolfendale, preprint). The striking similarity between the cosmic-ray distribution deduced by Stecker et al. (1975) and the supernova distribution in the galaxy (Ilovaisky and Lequeux 1972, Kodaira 1974) provides new evidence that supernovae produce the bulk of the cosmic-ray flux.

The galactic γ-rays are primarily the result of the decay of π^0-mesons produced in cosmic-ray interactions with interstellar gas (Kniffen et al. 1973). Their flux is therefore proportional to the product of gas density and cosmic-ray intensity integrated along the line-of-sight and the solid angle subtended by the γ-ray telescope. If a cosmic-ray flux distribution is assumed and Compton and bremsstrahlung γ-rays are also included in the calculation (a 30 per cent correction at most), one can calculate the flux expected to be observed by the SAS-2 γ-ray telescope of Fichtel et al. (1975) integrated over $\pm 10^{\circ}$ in galactic latitude and averaged over 5° longitude. This can only be done over the half of the galaxy for which the molecular cloud distribution has been determined (Scoville and Solomon 1975). The details of this calculation are given by Stecker et al. (1975). They found that a uniform cosmic-ray flux distribution leads to a

γ-ray flux which is a factor of ~2 too high compared to the observations in the anticenter direction and which is too low in the direction of the galactic center.

Using the same methods, a calculation of the γ-ray flux distribution can also be made under the assumption that the cosmic-ray distribution is proportional to the supernova remnant distribution in the galaxy, as would be expected if (1) supernovae are the principal source of cosmic rays, and (2) cosmic rays diffuse only a few hundred parsecs before leaking out of the galactic disk (Jokipii and Parker 1969, Ramaty, Reames and Lingenfielter 1970).

Using the supernova distribution obtained by Kodaira (1974) as representative of the galactic cosmic-ray flux distribution, the longitude distribution of γ-rays as would be observed by the SAS-2 telescope has been calculated. The results are shown by the histogram in figure 1 along with the data actually obtained by Fichtel et al. (1975), indicated by the vertical lines. The calculated distribution is in remarkable agreement with the data, providing strong support for the hypothesis that supernovae produce most of the observed cosmic rays. Calculations in further support of this conclusion may be found in Stecker et al. (1975).

A further refinement of these calculations can be made by considering the fine-scale clumpiness of the nearby molecular clouds. This generally leads to small corrections which account for some of the finer features in the γ-ray data, the most important of which is an additional flux in the 35° to 40° longitude range due to a large cloud (Kh3) which accounts for the apparent discrepancy between calculation and observations there (Puget and Serra, in preparation).

The supernova remnant distribution used here can be correlated with the distributions of various other population I objects to estimate the average age of the remnants. For this purpose, we turn to the detailed discussion of the correlation of gas and OB associations made recently regarding M31 (Emerson 1974). These results show that the surface densities of HII regions and atomic hydrogen (HI) are related by $\sigma_{HII} \propto (\sigma_{HII})^{2.23}$. For our own galaxy, due in part to optical depth effects, the HI distribution obtained from 21cm observations may be to some extent misleading in the inner galaxy (Scoville and Solomon 1975, Stecker et al. 1975). However, using the data of Mezger (1970) we find a correlation between the supernova remnant distribution and the HII region distribution of the form $\sigma_{SN} \propto (\sigma_{HII})^{0.4}$. Assuming, as for M31, $\sigma_{HI} \propto (\sigma_{HII})^{2.23}$, it then follows that $\sigma_{SN} \propto (\sigma_{HI})^{0.89}$. If the correlation between OB associations and HI gas is also expressed in the form $\sigma_{OB} \propto (\sigma_{HI})^{m}$, it is found that the older the association, the smaller the value of m (Emerson 1974). The decrease of this correlation with age is generally attributed to a spreading out of the stars in the OB associations with time, all the stars in the association having been spawned from the same cloud complex. The correlation defined by m = 0.89 is close to the mean correlation with gas of all OB associations and consistent with an age of 3 x 10^7 yr. Thus, it appears that the sources of galactic cosmic rays are young galactic population I objects, most likely to be supernovae. It is, in any case, apparent that the cosmic-ray distribution in the galaxy is determined by its own structure and evolution rather than by external sources.

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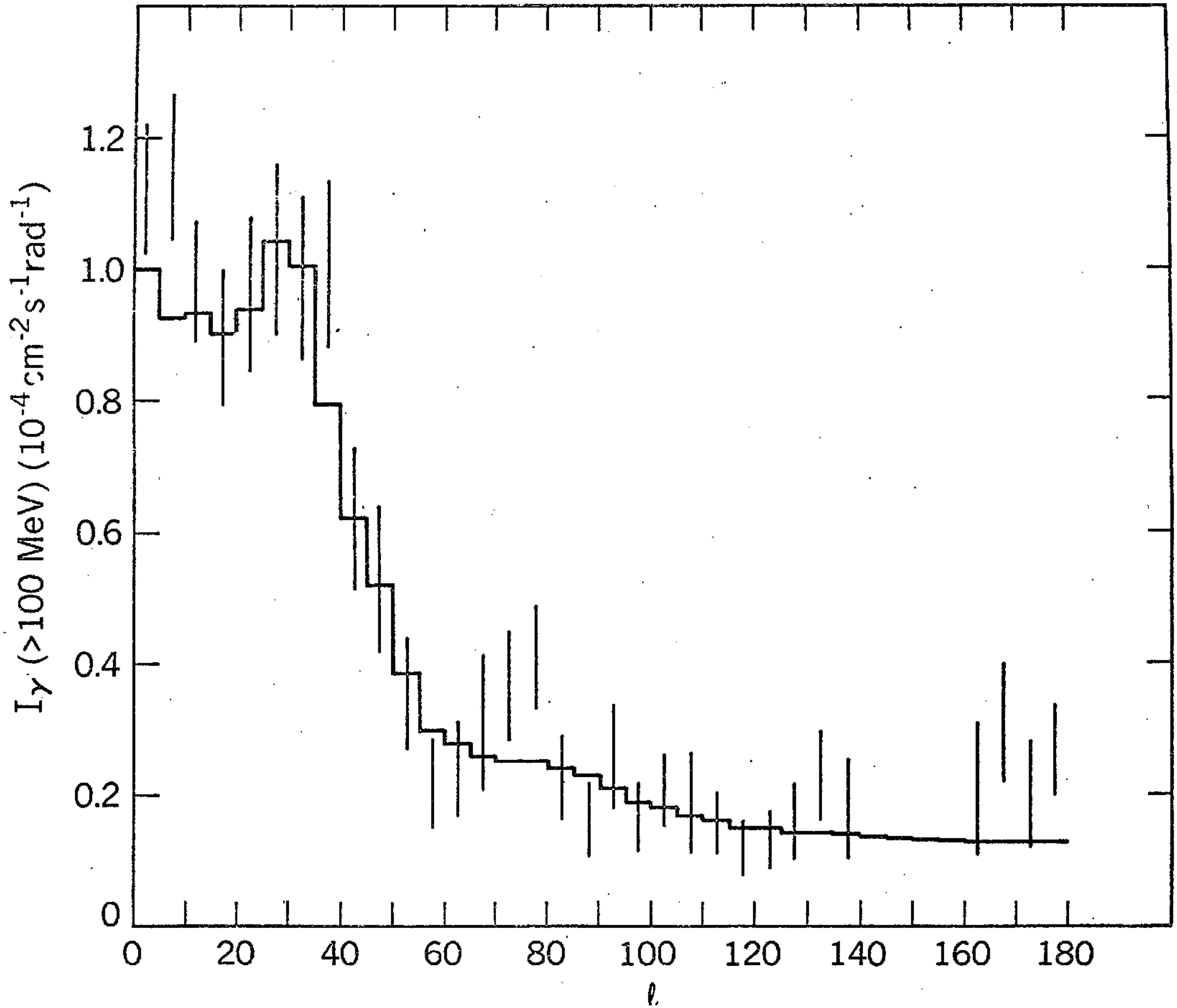
FIGURE CAPTION

Figure 1. Calculated longitude distribution of galactic γ-rays under the supernova origin hypothesis (histogram) compared with the observations of Fichtel et al. (1975) (vertical lines).



1.2
1.0
0.8
0.6
0.4
0.2
0
0
20
40
60
80
100
120
140
160
180
ℓ
I_γ (>100 MeV) (10^{-4} cm^{-2} s^{-1} rad^{-1})